

## NUMERICAL RESERVOIR MODEL OF THE TAKIGAMI GEOTHERMAL FIELD, OITA, JAPAN

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### **ABSTRACT**

We developed a conceptual model of the Takigami geothermal field and corresponding numerical models using the TOUGH2 simulator, rock types were assigned to each gridblock in several layers. Initial and boundary conditions were defined according to available data. The model, which covers a square area of 9.6 km by 9.6 km, with 3 km depth below sea level, consists of 12 horizontal layers, with layer thickness varying from 200 m to 800 m. For the optimum model, we estimated the permeability values of the various rock types, mass flow rates, enthalpies and locations of recharge zones. These were based on matching between computed temperatures at the wells and their measured temperature profiles before exploitation. A comparison between observed and calculated temperature profiles confirmed the validity of the conceptual model and provided the first stage of calibration of the 3-D numerical model. The iTOUGH2 simulator was used for the calibration. Our best model could successfully reproduce the initial temperature profiles of 13 wells located mainly in the production area. Overall, history-matching results for enthalpy production from the simulated model show an acceptable match with measurements in four production wells.

### **INTRODUCTION**

The Takigami geothermal field is located in the southwestern part of the Oita prefecture, Kyushu Island, Japan. Central Kyushu is intersected by a volcano-tectonic depression that has developed within a tensile stress field since the Neogene, resulting in Plio-Pleistocene to recent volcanism (Hase et al., 1985). The northeastern part of Central Kyushu, known as the Hohi region, is one of the most active geothermal areas in Japan

(Figure 1). Although the Takigami system lies within this very active Hohi geothermal region, there is no surface manifestation in the immediate area: The nearest hot springs are located 1–2 km north and east of the area. (Furuya et al., 2000). Geothermal exploration in the Takigami area began in 1979 with various surveys and drilling.

In and around the Takigami area, gravity and electromagnetic prospecting has been conducted since 1979, while resistivity logging began in 1981 (Aoki, 1988). These surveys confirmed the existence of three main layers in the resistivity structure of the field that extend laterally over the area. The intermediate layer has an extremely low resistivity, while the bottom layer has relatively high resistivity. The second, conductive layer is shallow and thin in the east, and deepens and becomes thicker to the west (Furuya et al., 2000).

A geochemical model of the Takigami area was discussed by Takenaka and Furuya (1991). Relatively low salinity and a low concentration of non-H<sub>2</sub>O, non-condensable gas in the produced steam characterize the Takigami geothermal fluids (Furuya et al., 2000). Itoi et al. (1993) obtained fairly good estimates of reservoir parameters by analyzing pressure interference tests using an infinite reservoir model for wells. Also, Gotoh (1990), in another study, stated that, with small decreases in reservoir pressure and temperature in the production zone, a production of 1850 t/h of geothermal fluid should be maintainable for more than 30 years

The Takigami power station, which started operation in November 1996 with a capacity of 25 MW, has increased its power to 27.5 MW as

of June 2010. Five production wells are located in the southwest part of the field; seven to ten reinjection wells are located in the northern part. Idemitsu Oita Geothermal Co., Ltd is in charge of production and reinjection operations, supplying separated steam to the power station, which is operated by Kyushu Electric Power Co., Inc.

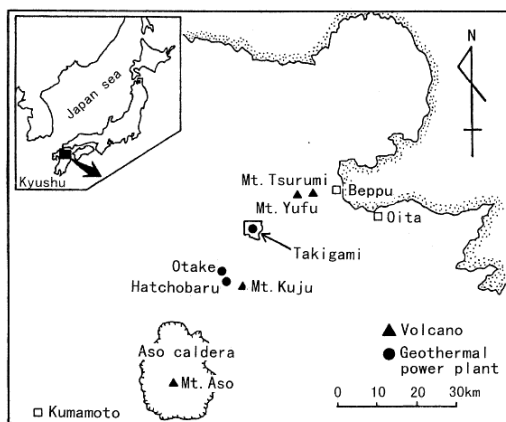


Figure 1. Map of the Hoho geothermal region, northeast Kyushu, showing the location of the Takigami area, the major Quaternary volcanoes and the Otake-Hatchobaru geothermal area (Furuya et al., 2000).

A three-dimensional numerical reservoir model of Takigami was developed by inverse modeling methods, using discharge enthalpies from production wells over ~11 years of the exploitation history (Nakatani et al., 2007). A wellbore flow model was coupled to the numerical reservoir model to improve the description of the physical system (Hozumi, et al., 2009).

We developed a new and improved model for the Takigami geothermal field, which draws from (and is enhanced by) previous experience. We recently conducted a simulation using the TOUGH2 code with the EOS1 module (Pruess, et al., 1999), with the objective of developing of natural state model of the field.

In addition to the numerical model, we also constructed a conceptual model of the field. As part of this effort, rock types were assigned to each block in several layers. Initial and boundary conditions were defined/assigned

based on the availability of data, and reasonable assumptions when such data were unavailable.

The objective of this study is to develop a numerical model of Takigami geothermal field by means of inverse modeling (history matching). This was achieved by matching model predictions to measurements of downhole temperatures (Jalilinasrabady et al., 2010). The simulation process required running the models to steady state and comparing the simulated data with the known or interpreted conditions in the system (Noorollahi et al., 2008). This is an iterative process that continues until a good match is obtained and requires changing model properties (such as permeability and inflow/outflow conditions) to obtain improved matches. With every set of reservoir properties, vertical heat flow and temperature distribution in each layer were also analyzed using Mulgraph (O'Sullivan, 1995). However, developing a reliable numerical reservoir model using this method can be time consuming.

## CONCEPTUAL MODEL

The Takigami area is surrounded by the late Pleistocene volcanoes of the Beppu-Shimabara Graben, which traverses middle Kyushu from east to west. This water-dominated field is characterized by the absence of surface geothermal manifestations, such as hot springs and fumaroles. There are a number of E-W, NW-SE, and N-S trending faults and fractures (Figure 2 and Figure 3).

The N-S trending Noine fault is important because it divides the area into eastern and western parts. The E-W trending faults, such as the Teradoko fault, are estimated to have a small vertical displacement. A high-permeability zone and a feed zone for the wells appear along these fault sets (Hayashi et al., 1988).

The geological structure of the Takigami geothermal field is as follows (Hayashi et al., 1988): A thick layer of Quaternary volcanic and associated rocks overlies the Tertiary Mizuwake andesite, which is estimated to overlay the basement. The Quaternary volcanic rocks are classified into four formations from top to bottom: the Noine-dake volcanic rocks, Kusu,

The thermal structure of this field is basically composed of three layers (Furuya et al., 2000). The first layer is isothermal (50°C), the second layer has a steep and constant thermal gradient because of its low permeability, and the third layer is characterized by high temperature that ranges from 160°C (in the northeast) to 250°C (in the southwest).

Geological map of the Teradoko area. The map shows various faults and lineaments, including the Teradoko Fault. A dotted area represents a basin-like structure. Hot water entries are marked with triangles and labeled with codes like TT1, TT2, TT3, etc. Structural trends are indicated by dashed lines. The map includes a legend and a scale bar (0 to 1 km).

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## NUMERICAL SIMULATION

According to the available literature on the Takigami geothermal field, and on the basis of studies of the field's conceptual model, we used iTOUGH2 to develop a three-dimensional numerical model. The model was calibrated using a trial-and-error approach, using available data on the natural-state conditions of the reservoir to obtain a good match between measurements and numerical predictions. Results of this match were used as initial parameters for inverse modeling.

iTOUGH2 allows us to conduct both natural-state and exploitation-history simulations. These simulations are carried out sequentially in a single run of iTOUGH2 (Finsterle, 2000). However, this method may require long computing times to achieve optimum values of parameters. To solve this problem, we first conducted a natural-state simulation. Then, both natural state and exploitation history were simulated sequentially, using the parameters estimated from natural-state simulation as the initial conditions for the exploitation simulations.

### Grid system and layers

A grid system was developed for modeling purposes. The grid system covers the square area of 9.6 km by 9.6 km, with 3 km depth below sea level (b.s.l.) (Figure 4). The model consists of 12 horizontal layers, with layer thickness varying from 200 m to 800 m. The coordinates of the system reflected correct surface elevations. Layers bb and cc had thicknesses of 300 m and 200 m, respectively; layers dd, ee, ff, gg, and hh were 200 m thick; layers ii, jj and kk were 400 m thick; and layer ll is the bottom layer, with a thickness of 800 m. Each layer has 414 gridblocks of various (non-uniform) sizes. Finer grids of 200×200 m were assigned to the areas corresponding to wells and power plant locations. The codes Mulgeom and Mulgraph (O'Sullivan et al., 1995) were used as pre-and post-processors.

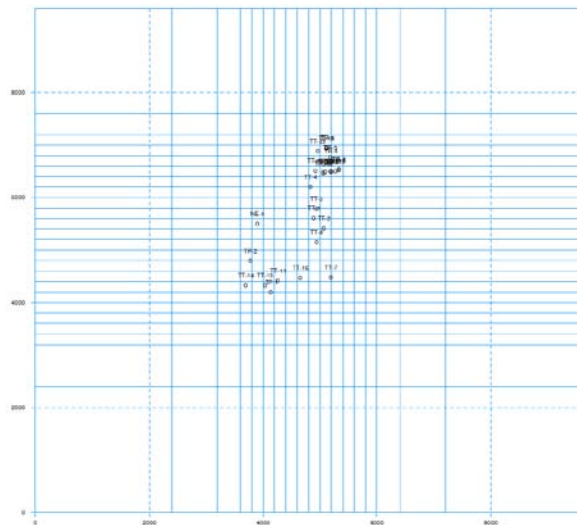


Figure 4. Grid system of the model.

### Rock properties

Density, permeability, thermal conductivity, porosity, and specific heat were taken into account as rock properties.

Table 1. Initial rock parameters.

Rock type	Intrinsic Permeability (m <sup>2</sup> )		Thermal Conductivity (W/mK)
	K <sub>XY</sub>	K <sub>Z</sub>	
ATM (A <sub>T</sub> )	1.00x10 <sup>-10</sup>	1.00x10 <sup>-10</sup>	3.0
NVR (N)	1.00x10 <sup>-14</sup>	1.00x10 <sup>-12</sup>	3.9
KLY (K)	1.00x10 <sup>-14</sup>	1.00x10 <sup>-15</sup>	2.6
LOW (L)	1.00x10 <sup>-18</sup>	1.00x10 <sup>-19</sup>	2.6
ALY (A)	1.00x10 <sup>-16</sup>	1.00x10 <sup>-17</sup>	2.5
MED (M)	1.00x10 <sup>-13</sup>	1.00x10 <sup>-14</sup>	3.6
MED1 (M <sub>1</sub> )	1.30x10 <sup>-12</sup>	5.00x10 <sup>-14</sup>	1.3
MED2 (M <sub>2</sub> )	1.00x10 <sup>-14</sup>	1.00x10 <sup>-15</sup>	1.3
MED3 (M <sub>3</sub> )	7.90x10 <sup>-15</sup>	3.20x10 <sup>-15</sup>	2.1
UTL (U)	1.00x10 <sup>-15</sup>	1.00x10 <sup>-13</sup>	1.5
LTL (L <sub>T</sub> )	1.00x10 <sup>-13</sup>	1.00x10 <sup>-16</sup>	2.3
MAL (M <sub>A</sub> )	1.00x10 <sup>-14</sup>	1.00x10 <sup>-16</sup>	4.0
UHW (U <sub>H</sub> )	2.00x10 <sup>-12</sup>	5.00x10 <sup>-14</sup>	1.8
UBAS (U <sub>B</sub> )	1.00x10 <sup>-14</sup>	1.00x10 <sup>-15</sup>	2.0
LBAS (L <sub>B</sub> )	1.00x10 <sup>-13</sup>	1.00x10 <sup>-15</sup>	2.7

The model requires estimates of rock properties as input data. These data were provided using the best available information on the geology, reservoir system, and fault characteristics of the system. One of these rock properties, the intrinsic permeability, plays a key role in achieving the most realistic model. Each layer of the grid was further subdivided into zones of different permeability values according to available data. Initial estimates of rock properties were based on the conceptual model and geologic media analogs. We used the locations of the main faults as well as the low- and high-permeability zones, to reproduce the

hydrogeological characteristics of the subsurface formation.

Initially, 18 rock types were assigned for the entire reservoir; Table 1 summarizes these rock types, indicating their permeability values in each direction after simulation. One reason for the large number of rock types was to investigate the system sensitivity to the properties of each layer and each zone, especially in the central part of the model, which covers the power station and all wells. As a result of optimization, some of the rock types in Table 1 that initially had different permeability values ended up with the same permeability values. This inverse modeling and parameter estimation method was very useful for understanding the system's sensitivity to each layer and each zone.

Permeability values vary between  $9.20 \times 10^{-21} \text{ m}^2$  and  $1.00 \times 10^{-12} \text{ m}^2$ . The rock types of MED, MED2 and MED3 represent high permeable zone such as the Noine fault. Table 2 shows the distribution of rock types in different layers. Porosity was specified as 10% for all rock types and a density of  $2500 \text{ kg/m}^3$  was assigned to all rock types.

#### **Calibration of the model**

The objective of the natural-state simulation is to reproduce the initial temperature and pressure distributions before any exploitation. The corresponding numerical simulations of the model need to cover a very long time, allowing the equilibration of the geothermal system. This involves running the simulation until approximately steady state conditions are reached, which means a simulation period for about 1 million years (Nakatani et al., 2007). The results of natural-state simulation were compared with the measured temperature data from 20 wells. The parameters estimated from the inverse modeling (matching) process were the permeabilities, flow rates, and enthalpies of recharges.

Table 2. Rock types in each layer of the model.

Layers	Rock Types
bb	N, M <sub>1</sub>
cc	K, M <sub>1</sub> , M <sub>A</sub>
dd	A, M <sub>1</sub> , M <sub>A</sub>
ee	A, U, M <sub>2</sub> , M <sub>A</sub> , M <sub>1</sub> , M
ff	U, L, M <sub>A</sub> , M <sub>1</sub> , M
gg	L <sub>T</sub> , L, M <sub>A</sub> , M <sub>1</sub> , M
hh	L <sub>T</sub> , M <sub>A</sub> , U <sub>B</sub> , L, M <sub>3</sub> , M <sub>1</sub> , M
ii	M <sub>A</sub> , L, U <sub>B</sub> , M <sub>1</sub> , M <sub>3</sub> , M
jj	M <sub>A</sub> , L, M <sub>1</sub> , U <sub>B</sub> , M <sub>3</sub> , M
kk	L <sub>B</sub> , U <sub>H</sub>

Table 3. Rock parameters in the final model

Rock type	Permeability (m <sup>2</sup> )		Thermal Conduct. (W/mK)
	K <sub>xy</sub>	K <sub>z</sub>	
ATM (A <sub>T</sub> )	$1.00 \times 10^{-10}$	$1.00 \times 10^{-10}$	3.0
NVR (N)	$1.50 \times 10^{-14}$	$3.90 \times 10^{-15}$	3.9
KLY (K)	$8.80 \times 10^{-17}$	$3.60 \times 10^{-15}$	2.6
LOW (L)	$9.20 \times 10^{-21}$	$2.70 \times 10^{-20}$	2.6
ALY (A)	$8.50 \times 10^{-16}$	$1.60 \times 10^{-20}$	2.5
MED (M)	$6.10 \times 10^{-14}$	$3.30 \times 10^{-13}$	3.6
MED1 (M <sub>1</sub> )	$4.80 \times 10^{-16}$	$1.30 \times 10^{-14}$	1.3
MED2 (M <sub>2</sub> )	$5.60 \times 10^{-14}$	$6.80 \times 10^{-13}$	1.3
MED3 (M <sub>3</sub> )	$1.80 \times 10^{-15}$	$1.90 \times 10^{-13}$	2.1
UTL (U)	$3.20 \times 10^{-15}$	$8.40 \times 10^{-18}$	1.5
LTL (L <sub>T</sub> )	$1.50 \times 10^{-15}$	$1.00 \times 10^{-19}$	2.3
MAL (M <sub>A</sub> )	$1.30 \times 10^{-15}$	$1.40 \times 10^{-14}$	4.0
UHW (U <sub>H</sub> )	$1.00 \times 10^{-12}$	$3.80 \times 10^{-15}$	1.8
UBAS (U <sub>B</sub> )	$1.00 \times 10^{-14}$	$3.60 \times 10^{-16}$	2.0
LBAS (L <sub>B</sub> )	$1.20 \times 10^{-15}$	$4.40 \times 10^{-16}$	2.7

As for initial conditions, it was assumed that all gridblocks were saturated with 15°C water and pressure equilibrated. The cap rock was assigned to the lowest initial permeability of  $1.0 \times 10^{-18} \text{ m}^2$ , and the maximum initial permeability was set at  $2 \times 10^{-12} \text{ m}^2$ . Thermal conductivities were in a range from 1.3 to 4.0 W/m<sup>2</sup>K.

A constant temperature of 15°C and pressure of 0.879 bar were applied to the layer above the top layer as a boundary condition. The other outer boundaries of the domain were assumed to be impermeable to mass and adiabatic to heat. The bottom layer (kk) was assigned two recharge zones. A high-temperature fluid recharge (R1) was imposed on the southeast to the finer grids at this part of the domain, and another recharge (R2) was imposed to the west of the finer grids of the model's bottom layer.

History matching was conducted using production and reinjection data covering 10 years of field operation. Estimated parameters of permeability and recharge flow rates with their enthalpies were modified. Table 3 summarizes the estimated permeability values. Fluid recharges are calculated to be 12 kg/s with an enthalpy of 946 kJ/kg for R1, and 15.7 kg/s with enthalpy of 1110 kJ/kg for recharge R2. A heat flux of 80 mW/m<sup>2</sup> was applied to all grids of the bottom layer. Figure 5 shows the initial and estimated values of rock types in the model.

## **SIMULATION RESULTS**

The constructed model was evaluated in an iterative manner, in order to create the initial conditions. Available subsurface data play an important role in constructing a realistic conceptual model. The adequacy of the model was evaluated by the quality of match of the natural-state conditions of the system to the model predictions. As mentioned before, permeability was a key parameter to be adjusted after each run of the model.

According to a suggested conceptual model modified from Takenaka and Furuya (1991), the subsurface fluid probably flows from southwest to northeast, and maintains chemical and thermal equilibrium with alteration minerals. The heat flow pattern was one of the criteria to be taken

into account in each run, in order to confirm flow directions.

The temperature distribution in each layer was also taken into account, in parallel with matching of measured temperature from the wells and computed results. The magnitude and locations of recharge zones were also adjusted in order to achieve satisfactory matches.

Appendix I compares the measured and simulated temperature profiles of ten wells. These plots were produced using calculated values of both the optimum and initial models. Relatively good matches were observed for Wells TT-1, TT-2, TT-3, TT-4, TT-8, TT-13, TT-14, TT-16 and NE-4. Well NE-5, located to the east of the Noine fault, also shows a good match, except at the depth of -100 m.b.s.l. In general, the model successfully reproduces the temperature profiles of 13 wells.

Figure 6 compares the enthalpy histories of four production wells at the Takigami geothermal power plant from 1996 to January 2007. The figure shows the measured enthalpy at Well TT-2 gradually decreasing over time, with the simulated values slightly lower than the measured ones for most of the simulated time. The measured enthalpy value of 7 kJ/kg is higher than the computed values at its maximum.

The model achieves good matches after year 2000 for Well TT-2. For Well TT-7, the simulated values are higher than the measured ones for all cases, and the simulated values are higher by 45 kJ/kg than the maximum measured values. The prediction of enthalpy at Well TT-13 is lower to that from the measured values; the thus, the measured enthalpy is 14 kJ/kg higher than the maximum simulation estimate. Well TT-14 shows a good match between simulated and measured enthalpies.

Overall, the history matching results based on enthalpy production show an acceptable match between measurements and numerical predictions in four production wells.

## **CONCLUSIONS**

A numerical model of the Takigami geothermal field was constructed using inverse analysis methods. Parameters such as permeabilities, flow rates, and enthalpies of recharges have been estimated. The best model can successfully reproduce the initial temperature profiles of 13 wells with natural-state simulations. Recharge zones were estimated to be 12 kg/s of 946 kJ/kg and 15.7 kg/s of 1110 kJ/kg at two different locations.

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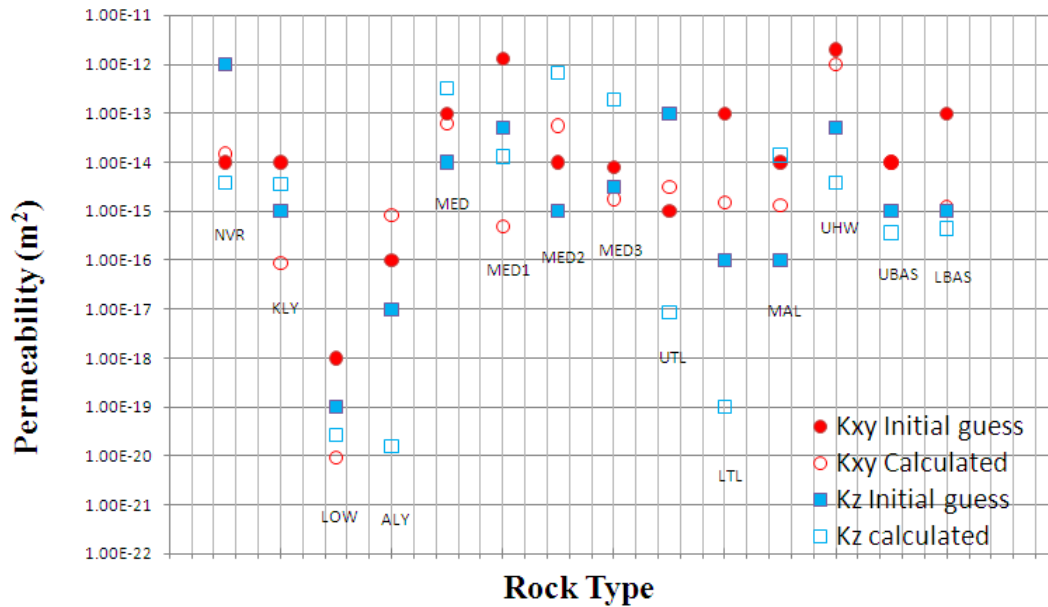
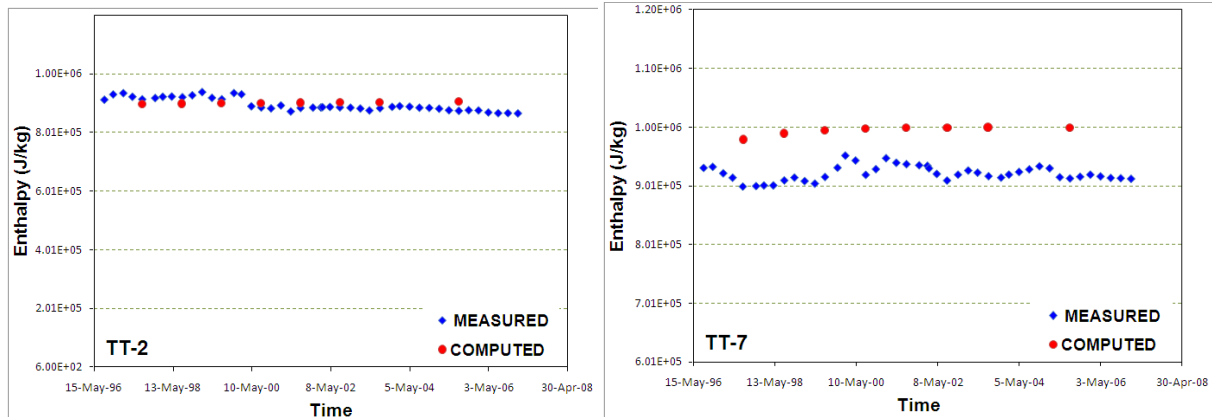


Figure 5. The initial and estimated values of rock types in the model.





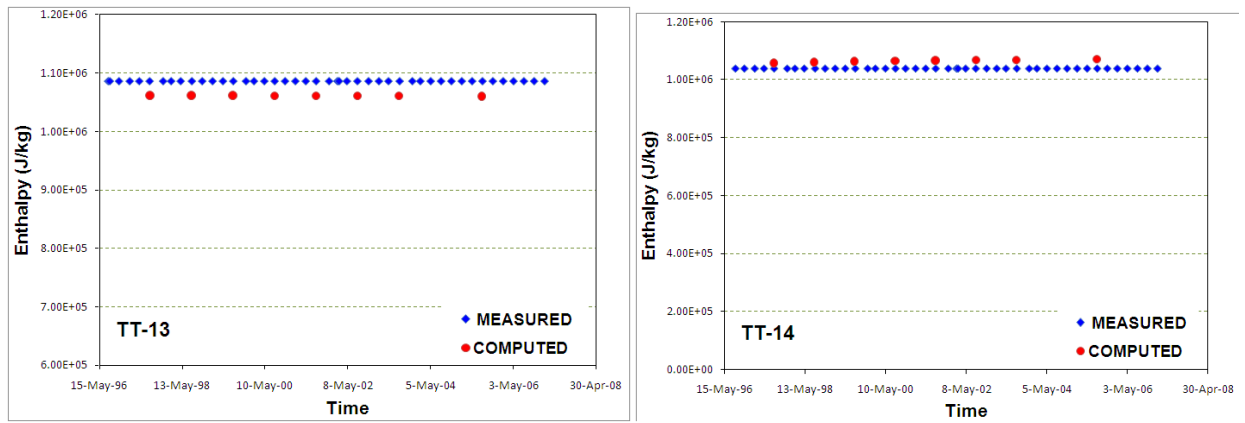


Figure 6. Measured and computed enthalpy of production wells TT-2, TT-7, TT-13 and TT-14.

Appendix I. Comparison between measured and simulated temperature profiles.

